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Land Surface Temperature Measurements from EOS MODIS Data

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1. Task Objectives

1) to complete a draft of the LST Algorithms Theoretical Basic Document by July 30, 1993;

2) to make detailed characterization of the thermal infrared measurement system including spectrometer, blackbody and radiation sources;

3) to make TIR spectral measurements of water and snow-cover surfaces with the MIDAC M2401 spectrometer;

4) to make conceptual and engineering design of an accessory system for spectrometric measurements at variable angles.

These objectives are based on the requirements by the MODIS Science Team and the unique challenge in the development of MODIS LST algorithms: to acquire accurate spectral emissivity data of land covers in the near-term and to make ground validations of the LST product in the long-term with a TIR measurement system.

2. Work Accomplished

2.1. MODIS LST Algorithm Theoretical Basic Document (ATBD)

The version 0 of MODIS LST ATBD was accomplished and submitted to the MODIS Team in early August, 1993 [1]. It will be revised after reviewing ATBD's of other MODIS Land products. Therefore, the content of the ATBD has not been included in this report.

2.2. Characterization of the TIR instrument System

The TIR instrument system to be used for measurements of land-surface emissivity and temperature consists of a TIR spectrometer from MIDAC Corp., a blackbody radiation source

from CI Systems, and a 486DX2-66 notebook computer. The CI blackbody has a clear aperture 7" by 7" and could operates at the blackbody temperature from 5°C to 75°C. According to the Operational Manual [2], the emissivity of the smooth blackbody surface is between 0.92 and 0.96 in the wavelength range 3-15 μm, its minimum is near 9.5 μm, the average emissivity is 0.953 and 0.946, in 3-5 and 8-12 μm, respectively. According to the calibration inspection report provided by the manufacturer, the signal-to-noise ratio (SNR) is 4×10^4, the accuracy is ±0.04 °C, the stability is ±0.003, ±0.01, and ±0.05 °C in the differential temperature ranges $\delta T < 10$ °C, $\delta T > 10$ °C, and $\delta T > 50$ °C, respectively, where δT refers to ambient temperature 23.3 °C. This stability should satisfy the requirement for testing SNR of the TIR spectrometer at a level of 10^3. Testing was started immediately after receiving the MIDAC TIR spectrometer in September. The measured system SNR including noise effects of the blackbody and the MIDAC spectrometer in the 11-12 μm window is about 2560 and 3400, at blackbody temperature 20 °C and 60 °C, respectively.

The spectral resolution of the spectrometric data after Fourier transformation could be chosen from 0.5, 1, 2, 4, 8, 16 and 32 cm^{-1}. A resolution of 4 cm^{-1} satisfies the requirement for the development of MODIS LST algorithm in most cases. The spectrometer works fine when it measures thermal radiation from the blackbody at room temperature and higher. The typical SNR is above 500 in the wavelength range 8-14 μm, and about 10-20 in the range 3.3-5 μm. So an accuracy of 0.5% could be achieved in the whole spectral range from 3.3 to 15 μm by taking average of 400 spectra. The spectrometer is capable to work in a high humidity situation because ZnSe beamsplitter and windows were used in the MIDAC spectrometer, and ZnSe is insoluble. The speed of the moving mirror in the interferometer could be selected so that interferogram could be collected at three speed modes of 20, 40, and 80Khz. At 40Khz, 4 interferogram spectra are collected per second at spectral resolution 4 cm^{-1}, so that 512 spectra (4.2Mb data) could be collected in about 2 minutes.

A 540Mb hard disk is used in the 486DX2-66 notebook computer so that there is enough disk space for storage of a large number (typically, 256 to 1024) of multiple spectra data for each single spectral measurement when more than 50 spectral measurements may be made in one day and for processing these data. The speed of the notebook enables to collect the spectrometer data at the high speed mode of 80Khz and to completes FFT of 256 interferograms at 4 cm^{-1} in about 2 minutes.

Two problems with the MIDAC spectrometer were identified in the first stage of testing: 1) the InSb/MCT sandwich detector from Graseby Infrared has a quite poor SNR in the medium

wavelength range 3-5 μm as the blackbody temperature is below 10°C and a significant channeling effect was observed, which is believed, due to multiple reflecting between the two detector elements; 2) there is no temperature control in the spectrometer so that the system response function decreases with time as the spectrometer gets warmer.

The sandwich detector was returned to MIDAC corp., and then returned to Graseby Infrared for repair. After its first repair, the sandwich detector is still noisy in the medium wavelength range although the channeling effect was improved slightly. In this situation, a MCT detector with a cold stop of 60° was provided by MIDAC Corp. as a tentative substitute. This tentative detector was used in all tests reported hereafter.

The total input power to the MIDAC spectrometer is about 40 W, which mainly is for operating the laser tube and electronics boards, and for scanning the moving mirror in the interferometer unit. The chassis is getting warmer after operation of the spectrometer for a few hours. It is easy to see the output interferogram is getting weaker as indicated by the peak value. Therefore, the data collection speed also becomes an important issue. A better SNR could be obtained at speed mode of 40Khz than at 20Khz. At speed of 40Khz, the instrument internal temperature may increase by 0.2 °C during 2 minutes which is needed to collect 512 interferograms at $4\,cm^{-1}$. But the higher speed mode of 80Khz does not provide further SNR improvement. The speed mode of 40Khz is an optimum speed in most cases considering of data volume and time used for making Fourier transformation of interferogram data.

2.3. Custom Improvements on the MIDAC Spectrometer

2.3.1. A gold mirror for change of the viewing angle

The MIDAC spectrometer is a forward looking instrument mounted on a tripod. Because liquid nitrogen (LN_2) is used to cool the detector the spectrometer may be tilted up or down no more than 30 ° without splash of the LN_2. A sandwich detector cooled by a small close-cycle refrigerator was planned to purchase for spectral measurements at different viewing angles in the whole semisphere. In theory, the InSb/MCT sandwich detector should have a better sensitivity in the spectral range 1-16 μm. But the P.I. did not have any real data to confirm it in the low temperature range until the MIDAC spectrometer with a LN_2 cooled sandwich detector was received. Two manufacturers of the sandwich detector were inquired about its real sensitivity data in the low temperature range and the impacts between two detector elements. No detail information is provided by these two companies. So the close-cycle cooled sandwich detector has not been put into order although its purchase request was approved in early 1993.

The P.I. believes that more information and real demonstration data are needed to submit a new purchase request. According to received information, an automatic scanning mirror system costs $25K and weights 20-30 pounds. So it is not acceptable. In order to make a temporary solution for up and down looking measurements, a commercial 4" diameter gold mirror priced at less than $500 was mounted with an aluminum frame which could be attached to and detached from the spectrometer. The gold mirror may be tilted so that the spectrometer could view up and down, and to the two sides. The spectral reflectivity of the gold mirror, as shown in Figure 1, is determined by taking ratio of the spectra of blackbody at temperature 64 °C collected directly by the spectrometer to the spectra collected with the gold mirror. It has minimum values of 0.92 and 0.94 at wavenumbers 1225 and 2450 cm^{-1}, respectively. Noted that strong atmospheric absorptions are in different locations, i.e., 1525 and 2355 cm^{-1}.

2.3.2. Reducing the spectrometer internal temperature

In order to characterize the effect of the instrument temperature on the system response, a thermistor was attached on the housing of the beamsplitter at a position which is close to the FOV of the detector. The temperature of the thermistor, which is referred as the instrument internal temperature, is then displayed at a resolution of 0.1 °C. It was found that the internal temperature increases to 38 or 30 °C in cases of the chassis cover on or off, respectively, after the spectrometer operates for 3-4 hours at ambient temperature 23 °C. The internal temperature increases by 1 °C in about every 10 minutes in the first two hours.

Several ways were tried to reduce the internal temperature. It appears that an easy and efficient way to cool the spectrometer is to put ice into plastic bags and to place these bags on the top and by the sides of the spectrometer chassis after necessary heat connections were made between the housing of the beamsplitter and the chassis. In this simple way the internal temperature could be reduced by more than 10 °C so that SNR in the medium wavelength range could be significantly improved. A quantitative analysis will be given in section 3.

2.4. In-house and Field Tests of the TIR Measurement System

Most tests were made in a room and backyard of the PI's house because there is no space available in the laboratory before moving to a new place in February, 1994. Intensive tests were made at different temperature conditions in day time and night time in order to characterize the system responses and performance of the MIDAC spectrometer, CI blackbody and several TIR radiation sources including commercial radiative heater, lamps and a slow cooker.

A field trip was also made to the Mammoth Lakes area, Sierra Nevada, CA during December 26, 1993 and January 1, 1994 for testing the spectrometer in the cold weather condition. TIR spectral measurements were made over several snow cover sites. Tests show that the spectrometer and notebook computer work well in the cold weather, even at temperature below freezing and relative humidity closes to 100 percent at night. Actually, the data acquired at low ambient temperatures have better SNR's given the same level of radiation to be measured.

The atmospheric temperature and water vapor profiles are needed in atmospheric corrections for ground-based calibration of the MODIS TIR bands and validation of the MODIS LST product. Ground-based TIR data could be better used for retrieval of the lower part of the profiles [3] while spacecraft-based TIR data could be better used to retrieve the upper part of the profiles. A retrieving model with the iterative method [4] has been implemented for a nonscattering atmosphere, and has been tested with sky radiance calculated by LOWTRAN7 with its built-in atmospheric profiles. It will be tested with real data from ground-based measurements. Because sky radiance is much weaker than emittance from most land covers, it is a real challenge to acquire good quality sky radiance data. The MIDAC spectrometer was tested to measure sky radiance by using a gold mirror in front of the spectrometer. The test data show some negative values of sky radiance at several narrow wavelength ranges. This means that the MIDAC spectrometer should be improved before it could be used for measurements of sky radiance and thermal radiation emitted from land surfaces at an extremely low temperature.

2.5. Relation between BRDF and Emissivity Measurements

As well known, accurate determination of surface emissivity needs measurements of its BRDF (bidirectional reflectance distribution function). The conventional method to measure surface emissivity by using an integrating sphere assumes that the reference surface and a sample surface have a similar BRDF pattern. Otherwise, the uncertainty in measured emissivity may be up to $\pm 5\%$ for IR spheres and $\pm 0.5\%$ for visible spheres in cases of mixed diffuse and nondiffuse samples and reference [5].

A so-called diffusely reflecting gold plate is usually used to measure the downward atmospheric radiation flux in the field and the environmental radiation in laboratory. But the BRDF of this kind of gold plate is close to the Lambertian pattern only when the incident radiation is from a direction close to the normal direction of the plate. Otherwise the Lambertian approximation could not be used to the gold plate, as shown in experiment data in section 3.

2.6. Other Activities

A conceptual design of a pointing system to be used for measurements of TIR BRDF was completed. The basic structure of the pointing system is a 3.3M diameter hoop mounted horizontally on 4 legs, serving as a track for a vertical semicircular structure with 1.65M radius which rotates on the track about the hoop's vertical axis, above the hoop. The vertical semicircle in turn forms a track for a carriage which rolls along the circumference of the semicircle, about the semicircle's horizontal axis. Thus the carriage can be positioned anywhere on a half spherical surface. A locking mechanism will allow the carriage to be fixed in place. The carriage will serve as a mount for the spectrometer looking inward toward the center of the semisphere. The requirement for pointing accuracy is specified as ±1°. Three machine shops were invited to provide quotations for engineering design and fabrication of this pointing system.

I attended the ASTER U.S.-Japan Joint Science Team meeting, November 8-12, 1993 in Tokyo, Japan, and made a progress report on development of MODIS LST algorithm and characteristics of the MIDAC TIR spectrometer.

3. Analysis

3.1. SNR vs the internal temperature

Multi-spectra were collected at each given blackbody temperature in the range from 5 to 60 °C. Then the mean and standard deviation of the spectra could be calculated at different blackbody temperatures. Test results indicate that the SNR of the MIDAC spectrometer is limited by the background radiation in the current configuration with the tentative MCT detector, as shown in Figure 2. Figure 2(a) shows the standard deviation of spectra collected at instrument internal temperature 30.4±0.1 °C. Another set of results from spectra collected at internal temperature 15.9±0.8 °C is shown in Figure 2(b). The SNR in the medium wavelength range 3.3-5 μm increases more than 100% as the internal temperature reduces from 30.4 to 15.9 °C.

3.2. Dependence of the system response function on the internal temperature

The radiance values calculated from the blackbody temperature and measured values indicate a significant dependence of the system spectral response function on the instrument internal temperature, as shown in Figure 3. The system response function reduces by 25-35% as the internal temperature increases by 11 °C, so the change rate of the response function with the temperature is about 2.3-3.2% / °C.

3.3. Non-linearity of the system response function

A significant non-linearity is also found in the system response function, especially in the medium wavelength range, as shown in Figure 4. A quadratic form of response functions is required to present the relation between calculated radiance based on the blackbody temperature and the measured values from the spectrometer. The residual error is less than 0.5% without considering the emissivity correction of the blackbody in the whole spectral range from 660 to 3000 cm^{-1}, or less than 0.1% execpt narrow ranges at both ends.

There are at least three reasons for the nonlinearity of the system response function:

1) The cold stop of the tentative detector is 60°, which is significantly larger than the field-of-view 41° that is extended by the output port of the beamsplitter through the focusing mirror in front of the detector;

2) The ZnSe window of the dewar is not anti-reflecting (AR) coated so that about one third of incident thermal radiation is reflected away from the window and some part of the reflected radiation will be scattered back into the detector. This part of the radiation contributes an interferogram with different phase compared to the preliminary interferogram.

3) The emissivity of the blackbody surface is less than 1 so that the radiance from the blackbody consists of two parts: thermal infrared radiation emitted by the surface and environmental radiation reflected by the surface. Before BRDF of the blackbody surface is determined, we can only make a qualitative estimation. Taking the emissivity effect into considerations, the calculated radiance will be slightly smaller at temperatures above the ambient temperature or slightly larger at temperatures below the ambient temperature. Thus the non-linearity shown in Figure 4 should be slightly reduced at the upper end but slightly increased at the lower end.

3.4. TIR spectra examples of snow cover, ice-water surfaces and sky radiance

Figure 5 shows the TIR spectra of a snow cover site in south of Mono Lake in Serria Nevada, CA, collected in the time period 1:53-2:17pm on December 27, 1993. Separate spectra were collected for a snow surface and a gold plate under sunshine and in shadow, respectively. The unexpected features in the gold-plate spectra in the wavenumber range 600-1300 cm^{-1} are due to the low sensitivity of the spectrometer in this range and the effect of the solar beam shield

that is not far enough from the gold plate.

Figure 6 shows the spectra of sky radiance, snow surface, ice-water surface, LN_2 container, and blackbody at temperature 5°C, collected in a cloudy atmospheric condition during 7:20-7:41pm on December 28, 1993 at a location near the dorm's porch at the Sierra Nevada Aquatic Research Laboratory, University of California. The ice-water surface refers to a water surface in a plastic container filled with water and ice cubes, which is covered by a metal mesh beneath the water surface. The water surface is very close to the ice cubes so that ist temperature is believed close to 0°C. Then the snow-surface temperature could be well estimated if the calculated value of snow-surface emissivity [6] could be used. The sky radiance is relative high because of clouds, but there are still some negative values.

It is not possible to calculate spectral emissivities of snow-surface and ice-water surface from above data at this time because the downward atmospheric radiance was not been measured with a reasonable accuracy.

3.5. The reflectivity of a gold plate in different directions

In order to measure the angular dependence of the reflectivity of a so-called diffusely reflecting gold plate, the thermal infrared radiation from a commercial radiative heater is exposed on the gold plate at a zenith angle of about 65°, or is shielded away from the plate with an aluminum sheet, and the center of the gold plate is viewed by the spectrometer at about the same zenith angle in the principal plane and in the plane 90 degree from the principal plane. A relative reflectance is calculated from S_h, the spectra with the radiation from the heater, and S_0, the spectra without the heater radiation, as $(S_h - S_0)/S_0$. The ratio between relative reflectances in these two geometric conditions is given in Figure 7. Since the largest viewing angle of MODIS on the Earth surface is about 65°, this experiment gives an useful information: the so-called diffusely reflecting gold plate could not be used to estimate the downward atmospheric radiation for atmospheric corrections if its BRDF is unknown.

3.6. Directions of the potential improvements

The MIDAC spectrometer will be improved in the following directions: 1) using a detector with a cold stop of 40°; 2) using a ZnSe window with AR coating in the detector dewar; and 3) to stablize the beamsplitter housing at a low temperature. The minimum goal of these improvements is to achieve a SNR more than 20 at target surface temperature -10°C in the whole spectral range from 600 to 3000 cm^{-1}. The ultimate goal is to obtain sky radiance data with a reasonable SNR.

4. Anticipated Future Actions

1) to review all MODLAND ATBD's and to revise the LST ATBD before the end of February when it will go out for external review.

2) to improve the NSR of the MIDAC spectrometer.

3) to build a pointing system for spectrometric BRDF measurements.

4) to make emissivity and temperature measurements of land-cover samples with the MIDAC spectrometer and the pointing system.

5) to make radiative transfer simulations for the development of MODIS LST algorithm based on measured BRDF and emissivity values of land-surfaces.

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[5] L. M. Hanssen, "Effects of restricting the detector field of view when using integrating spheres," *Appl. Optics*, vol. 28, no. 11, pp. 2097-2103, 1989.

[6] J. Dozier and S. G. Warren, "Effect of viewing angle on the infrared brightness temperature of snow," *Water Resour. Res.*, vol. 18, no. 5, pp. 1424-1434, 1982.

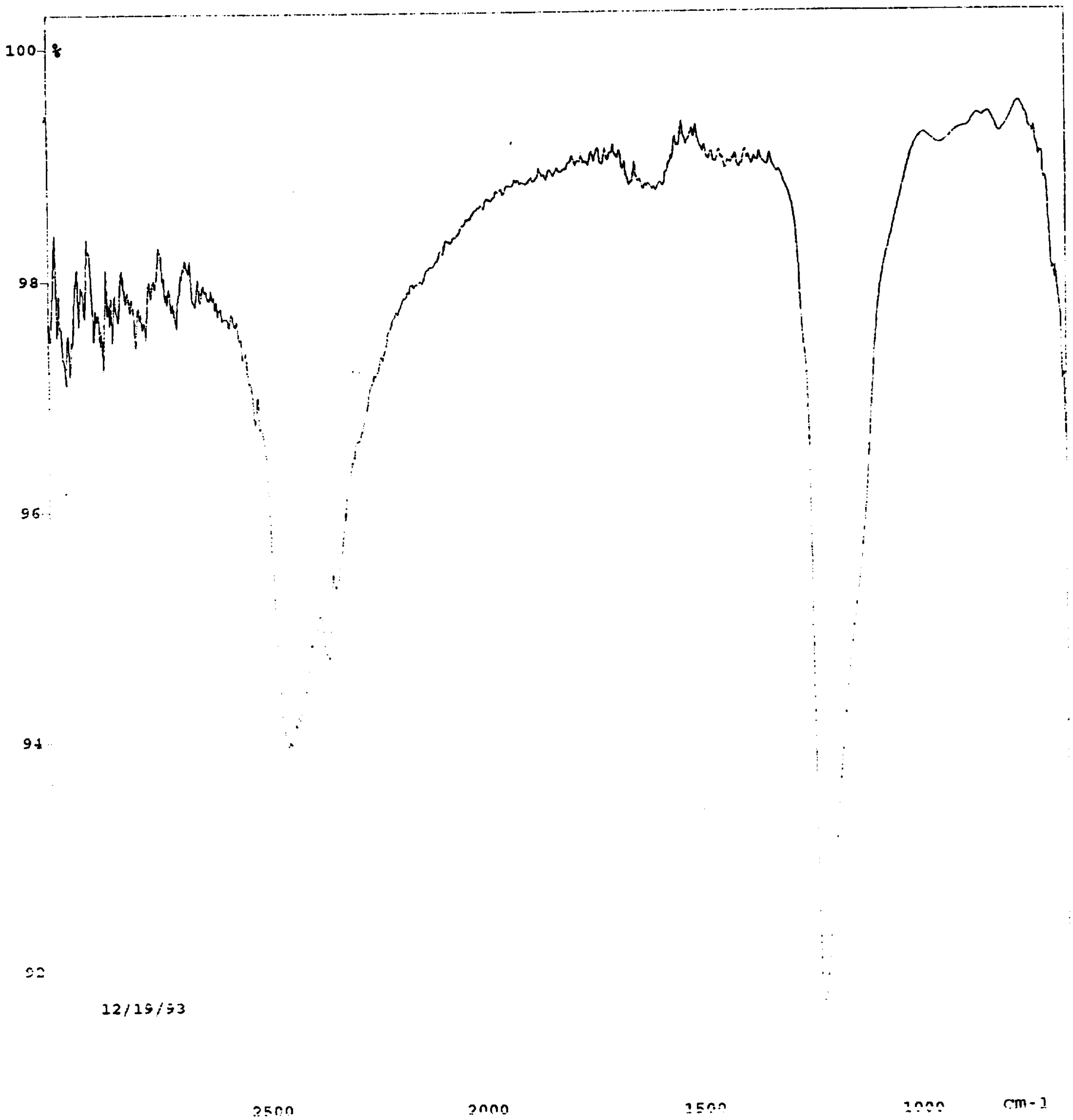

Figure 1   Reflectivity of a gold mirror calculated from measured spectra.

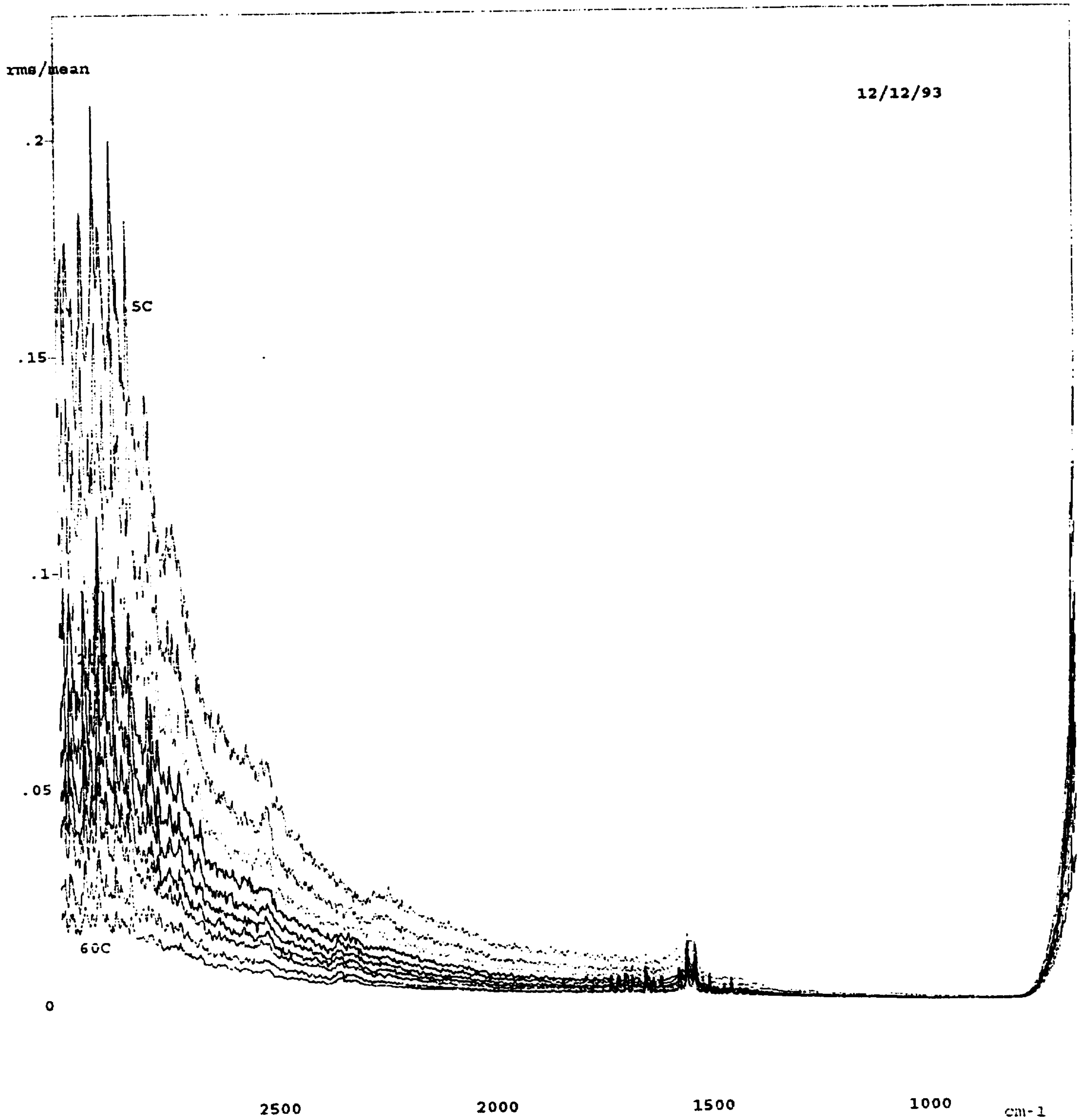

Figure 2a. Standard deviations of blackbody spectra at different temperatures (Tin = 30.4+-0.1 C).

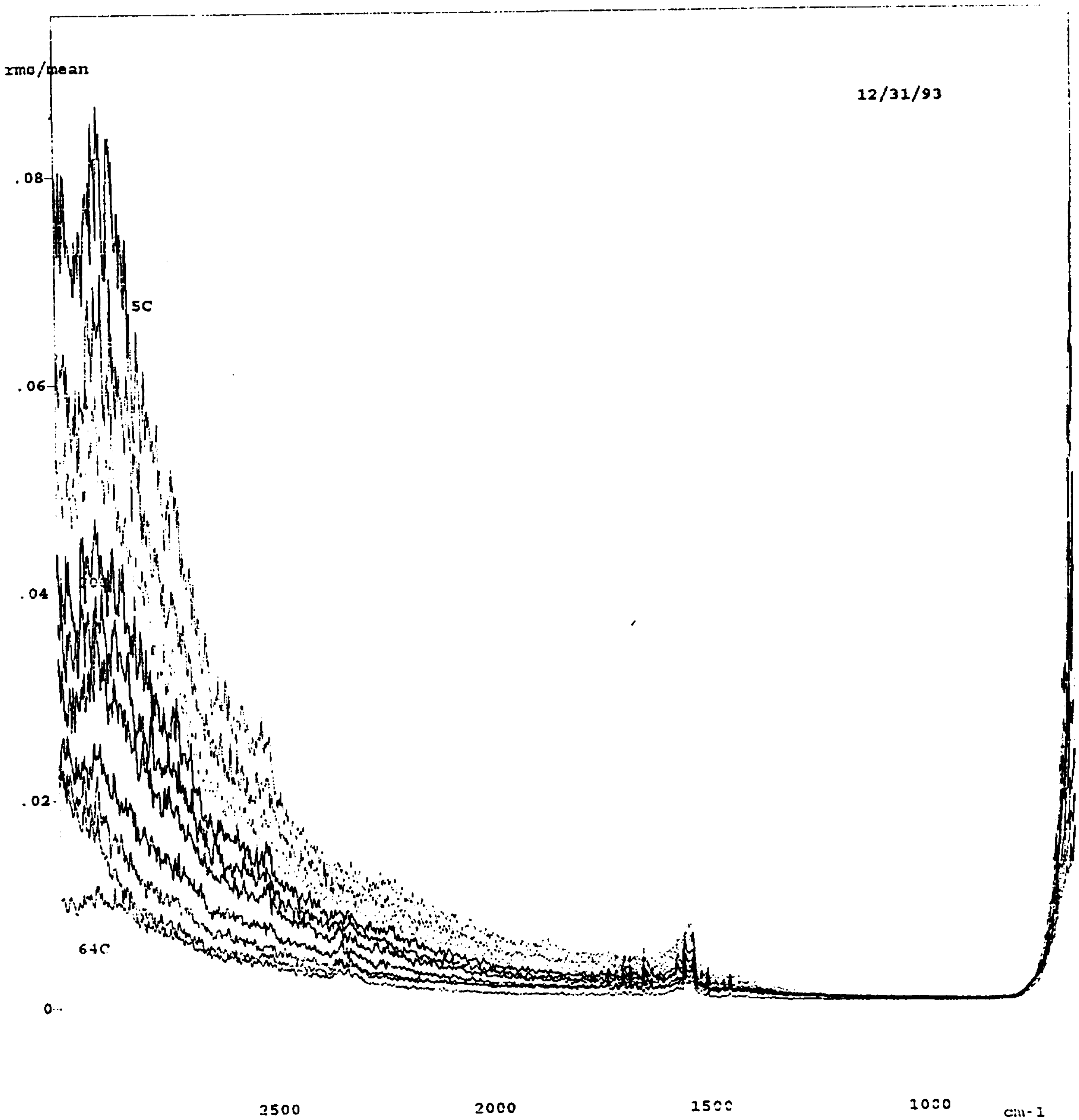

Figure 2b. Standard deviations of blackbody spectra at different temperatures

(Tin = 15.9+-0.8 C).

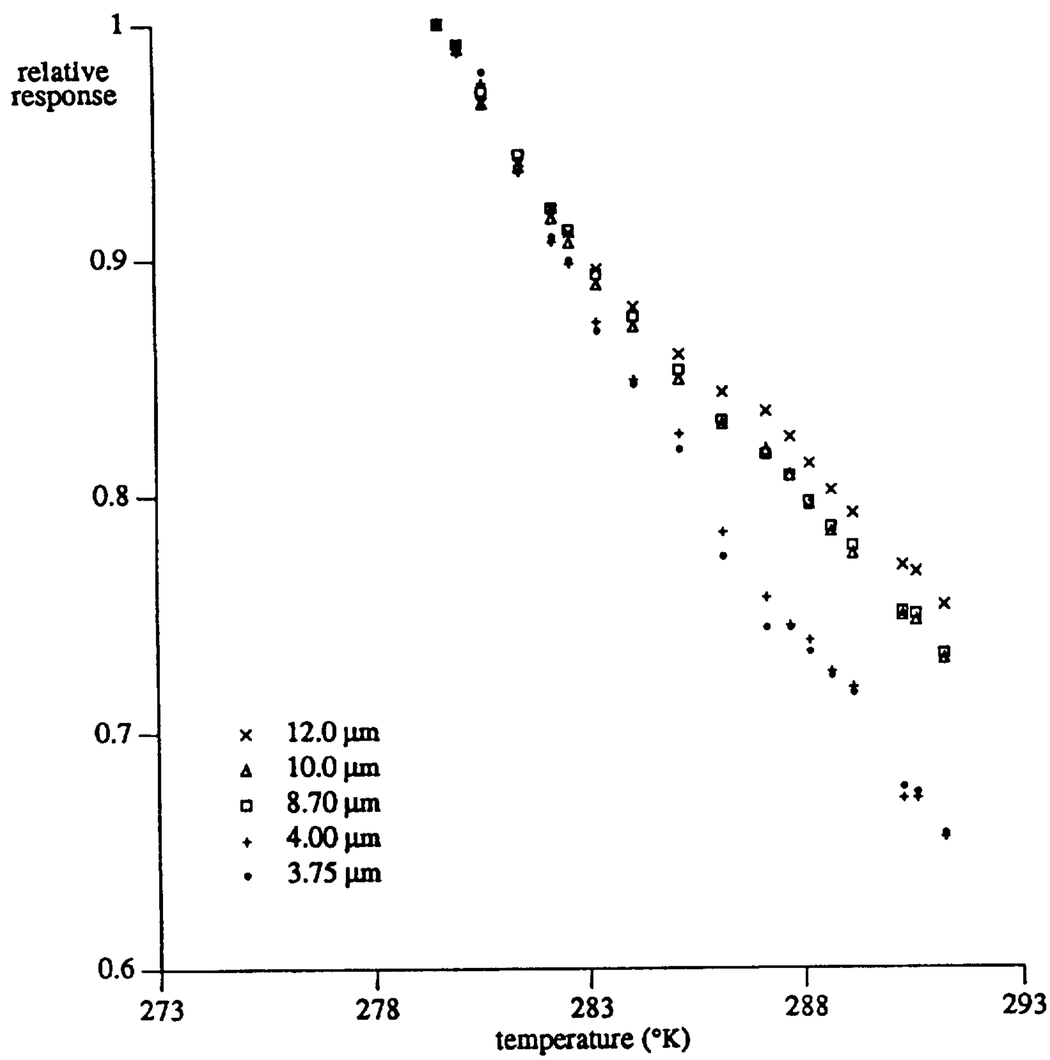

Figure 3. The effect of spectrometer internal temperature on response function.

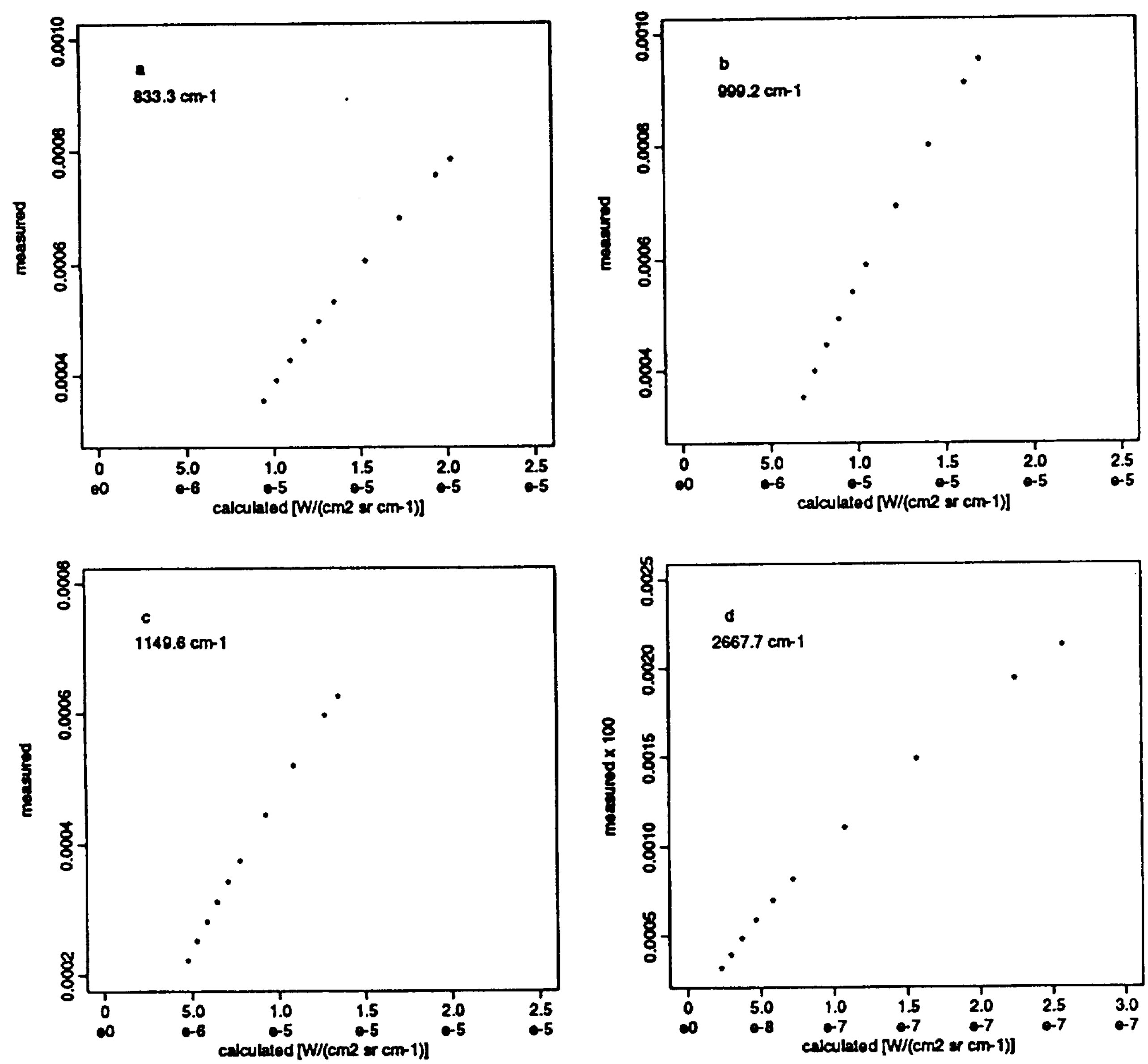

Figure 4. The non-linear relation between radiance values calculated from the blackbody temperature and measured values.

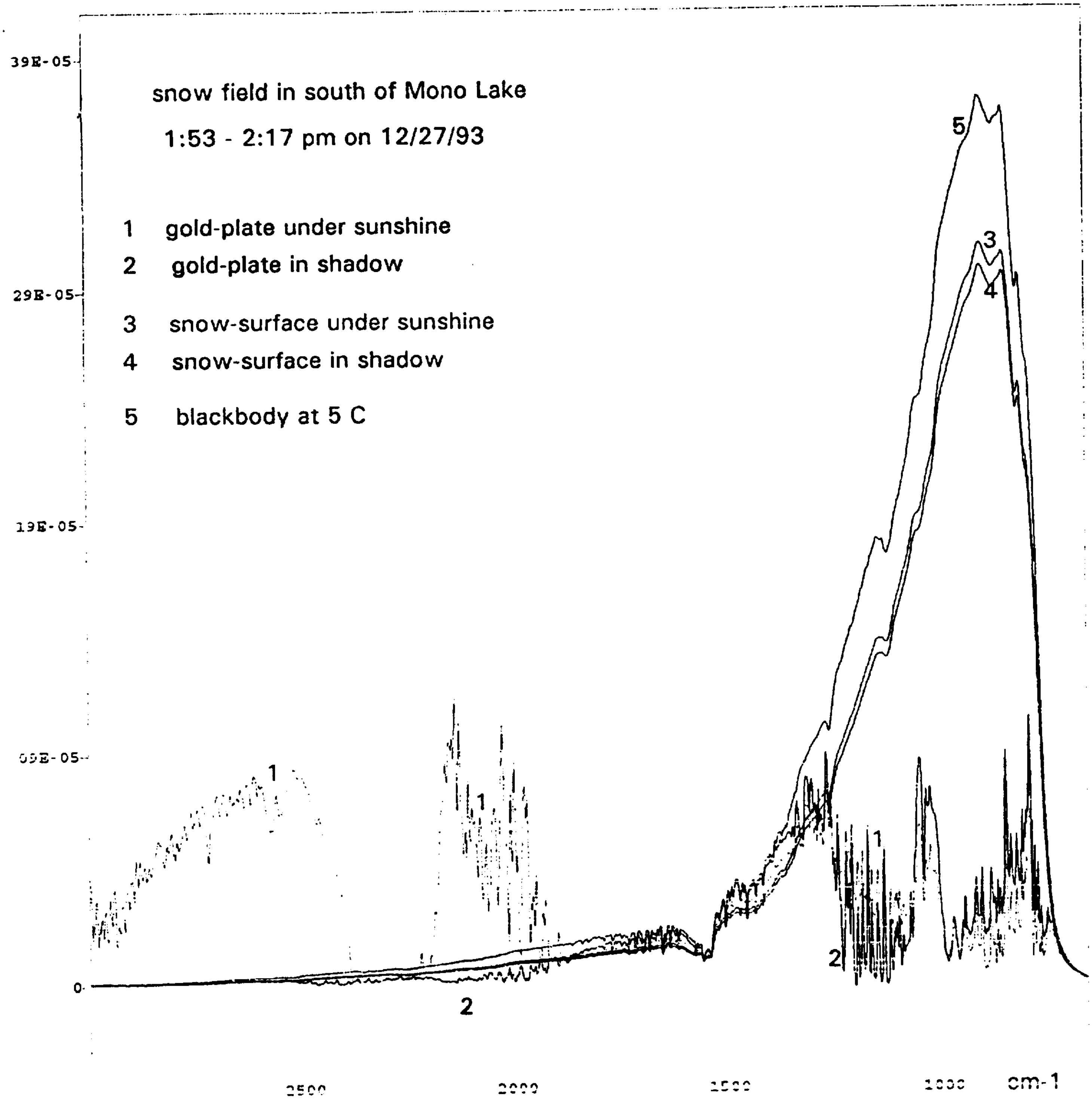

Figure 5. TIR Spectra of snow-surface and diffusely-reflecting-gold-plate under sunshine and in shadow, respectively.

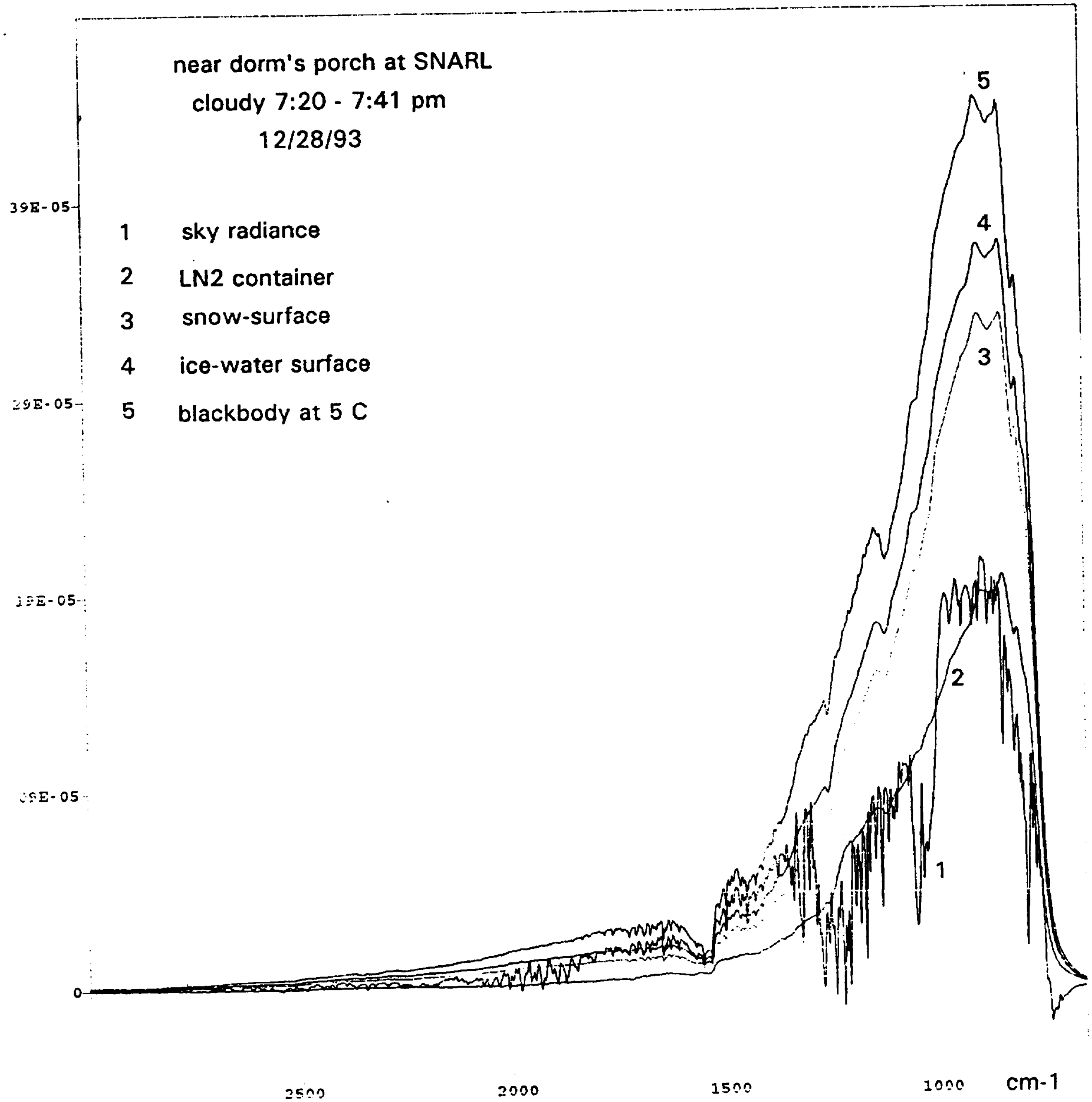

Figure 6. TIR Spectra of snow-surface, ice-water surface, and sky radiance.

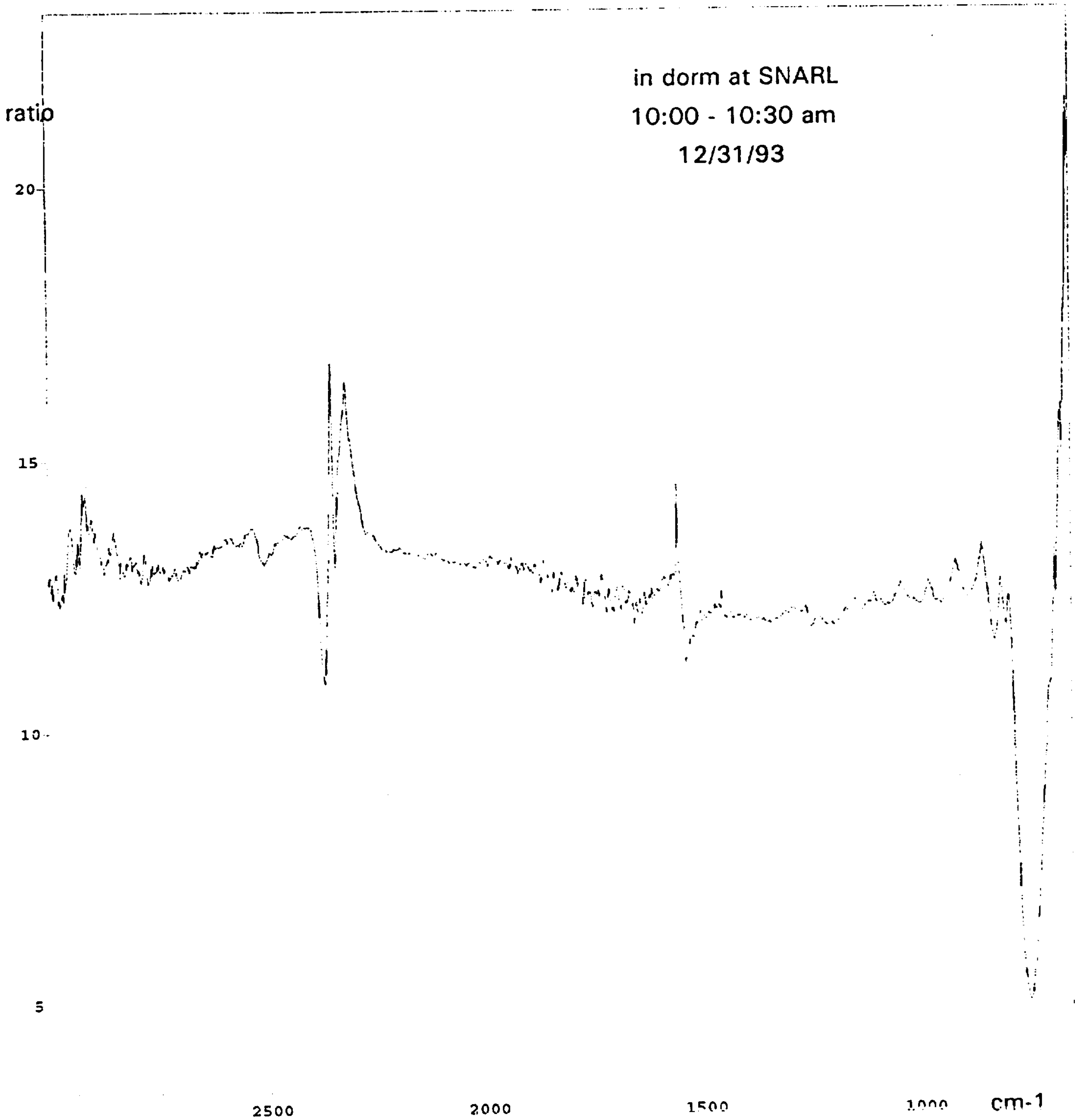

Figure 7. The ratio of relative reflectances of a gold-plate in the principal plane to that 90 degree from the principal plane.